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Lambert et al.

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(54) **SEISMIC SYSTEM WITH GHOST AND MOTION REJECTION**

(75) Inventors: **Dale J. Lambert**, Mandeville, LA (US); **André W. Olivier**, River Ridge, LA (US); **Robert E. Rouquette**, Covington, LA (US)

(73) Assignee: **ION Geophysical Corporation**, Houston, TX (US)

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(51) **Int. Cl.**
G01V 1/18 (2006.01)
G01V 1/20 (2006.01)

(52) **U.S. Cl.**
USPC **367/178**; 367/179

(58) **Field of Classification Search**
USPC 367/20, 24, 178, 153, 154; 181/122
See application file for complete search history.

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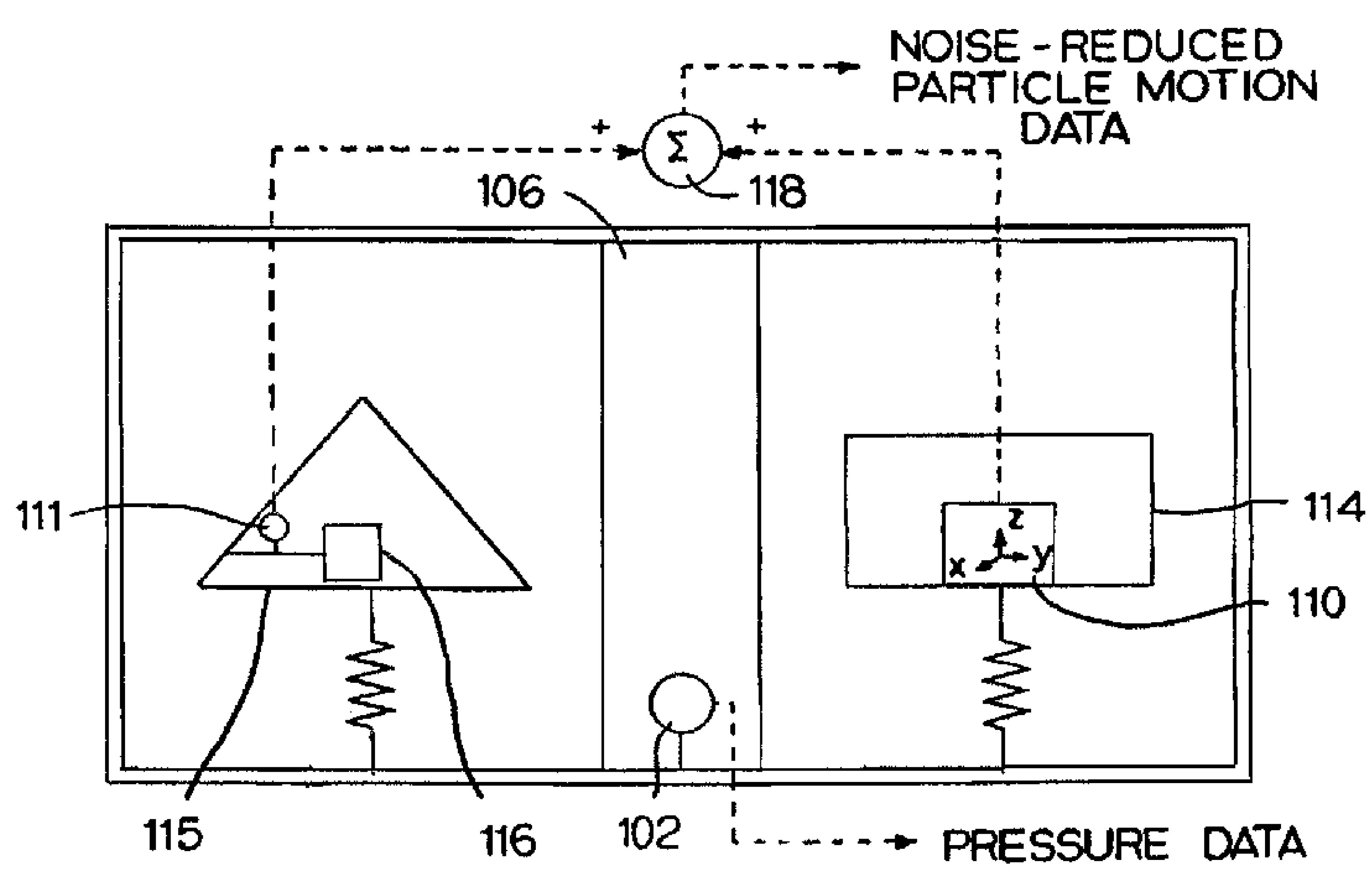
Primary Examiner — Isam Alsomiri
Assistant Examiner — Hovhannes Baghdasaryan
(74) *Attorney, Agent, or Firm* — James T. Cronvich

(57) **ABSTRACT**

An underwater seismic system for reducing noise due to ghost reflections or motion through the water from seismic signals. The system includes two motion sensors. One sensor has a first response and is sensitive to platform-motion-induced noise as well as to acoustic waves. The other sensor has a different construction that isolates it from the acoustic waves so that its response is mainly to motion noise. The outputs of the two sensor responses are combined to remove the effects of motion noise. When further combined with a hydrophone signal, noise due to ghost reflections is reduced.

19 Claims, 8 Drawing Sheets



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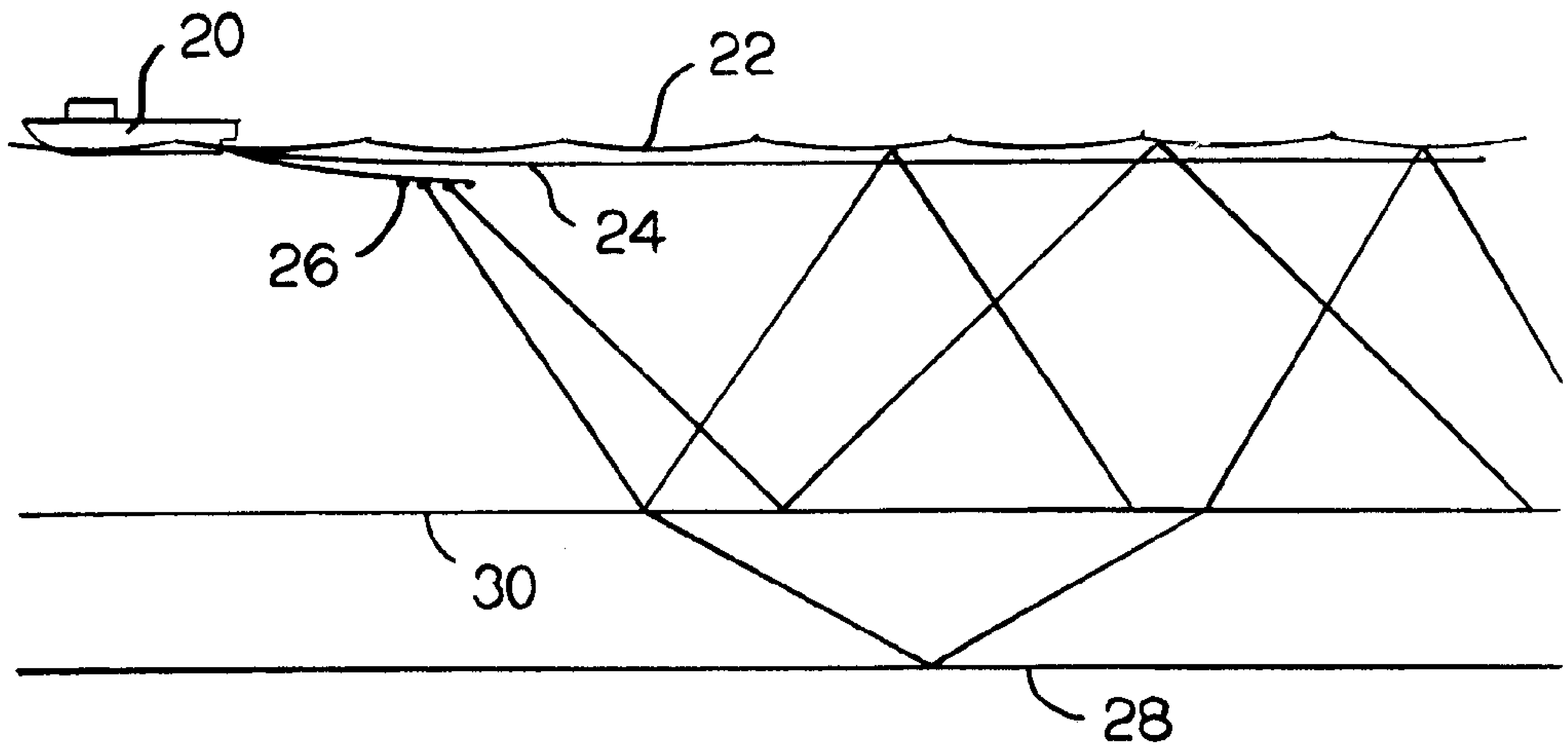
20
22
24
26
30
28

FIG. 1

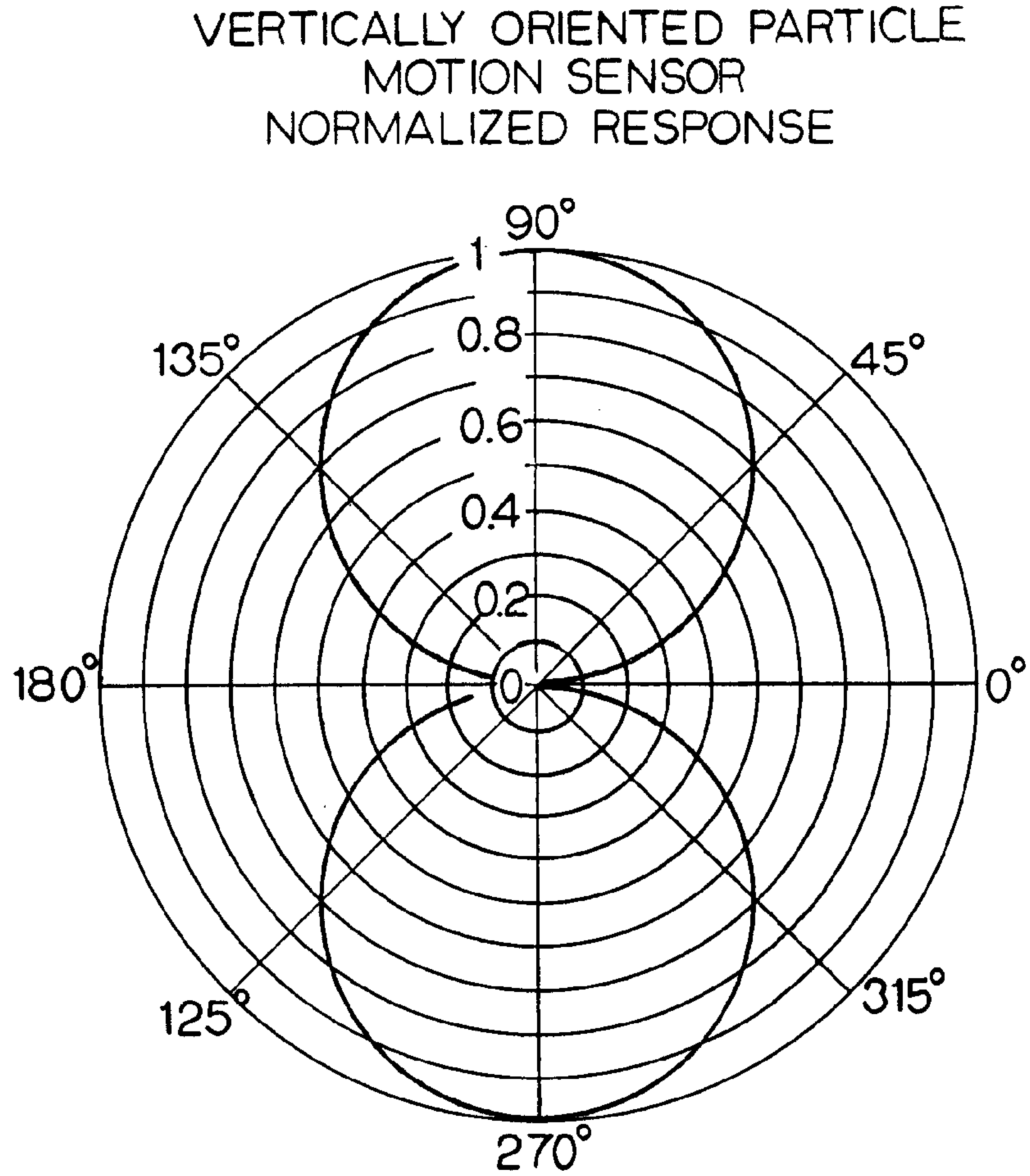
VERTICALLY ORIENTED PARTICLE
MOTION SENSOR
NORMALIZED RESPONSE
90°
1
0.8
0.6
0.4
0.2
0
135°
45°
180°
0°
125°
315°
270°

FIG. 2

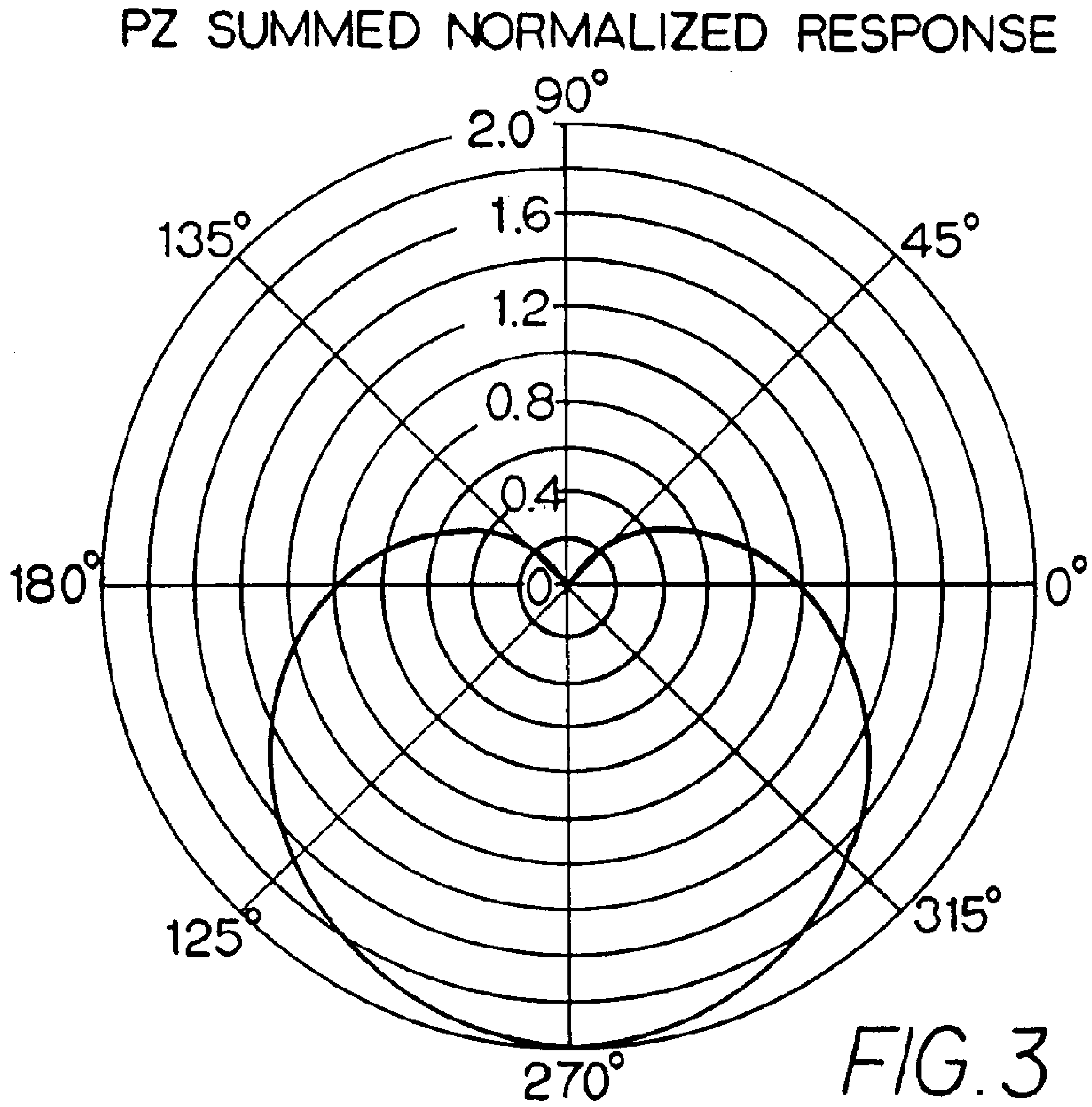

FIG. 3

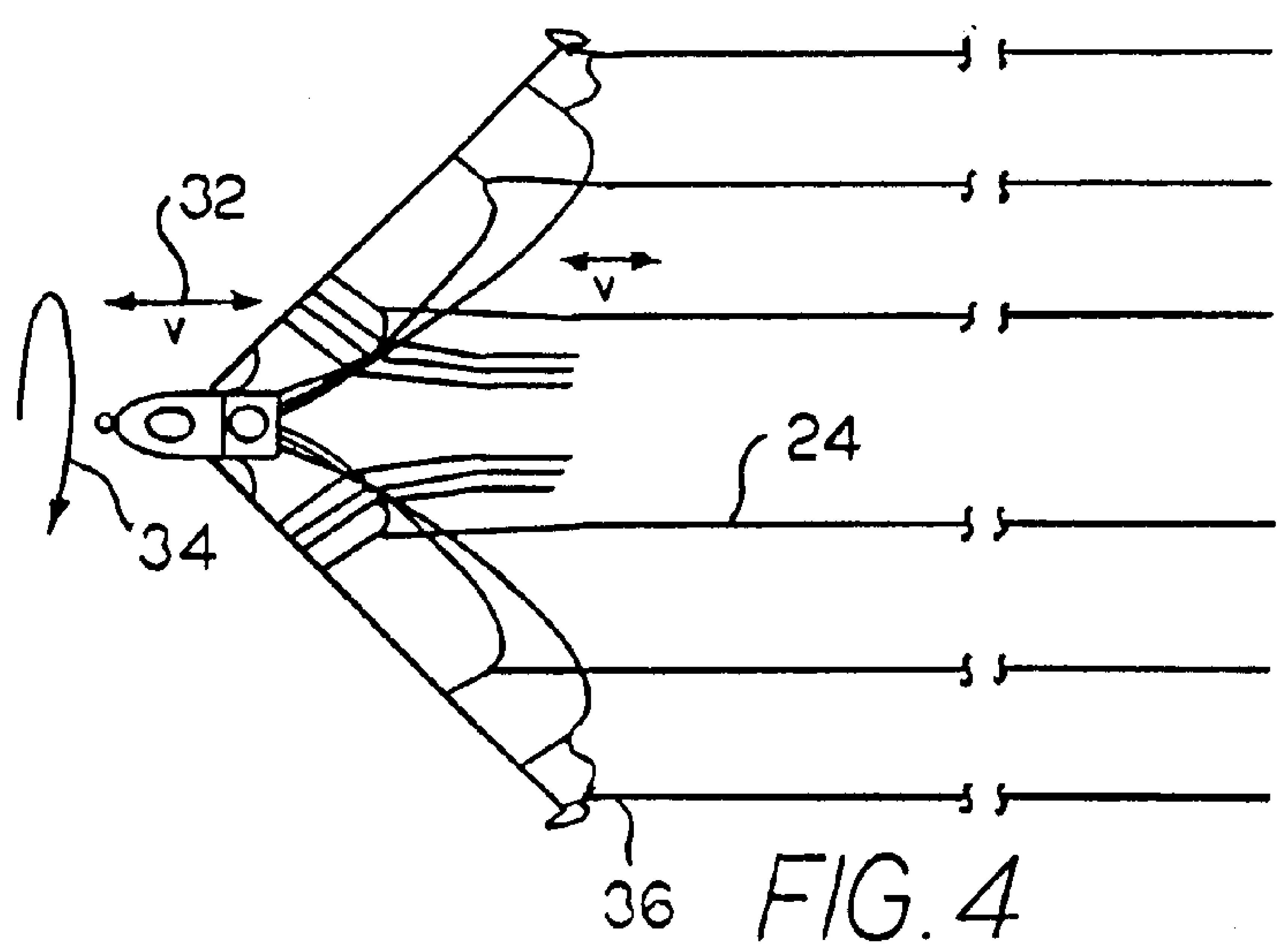

FIG. 4

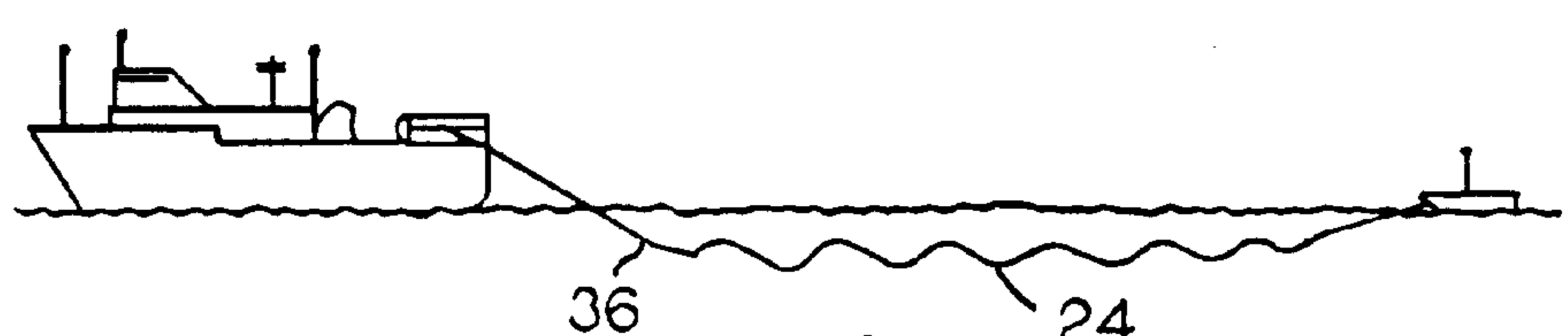

FIG. 5

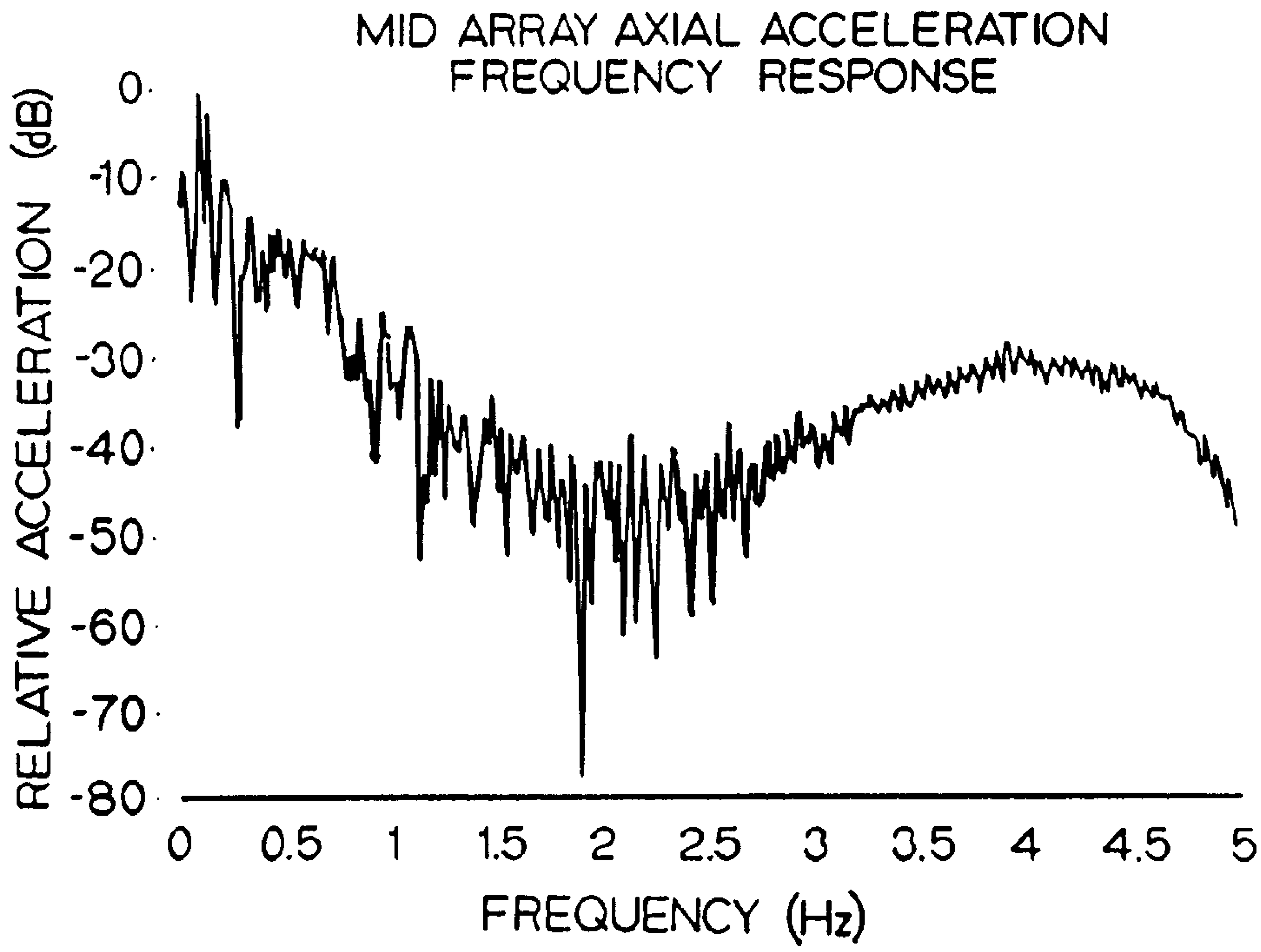
MID ARRAY AXIAL ACCELERATION
FREQUENCY RESPONSE
RELATIVE ACCELERATION (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
FREQUENCY (Hz)

FIG. 6

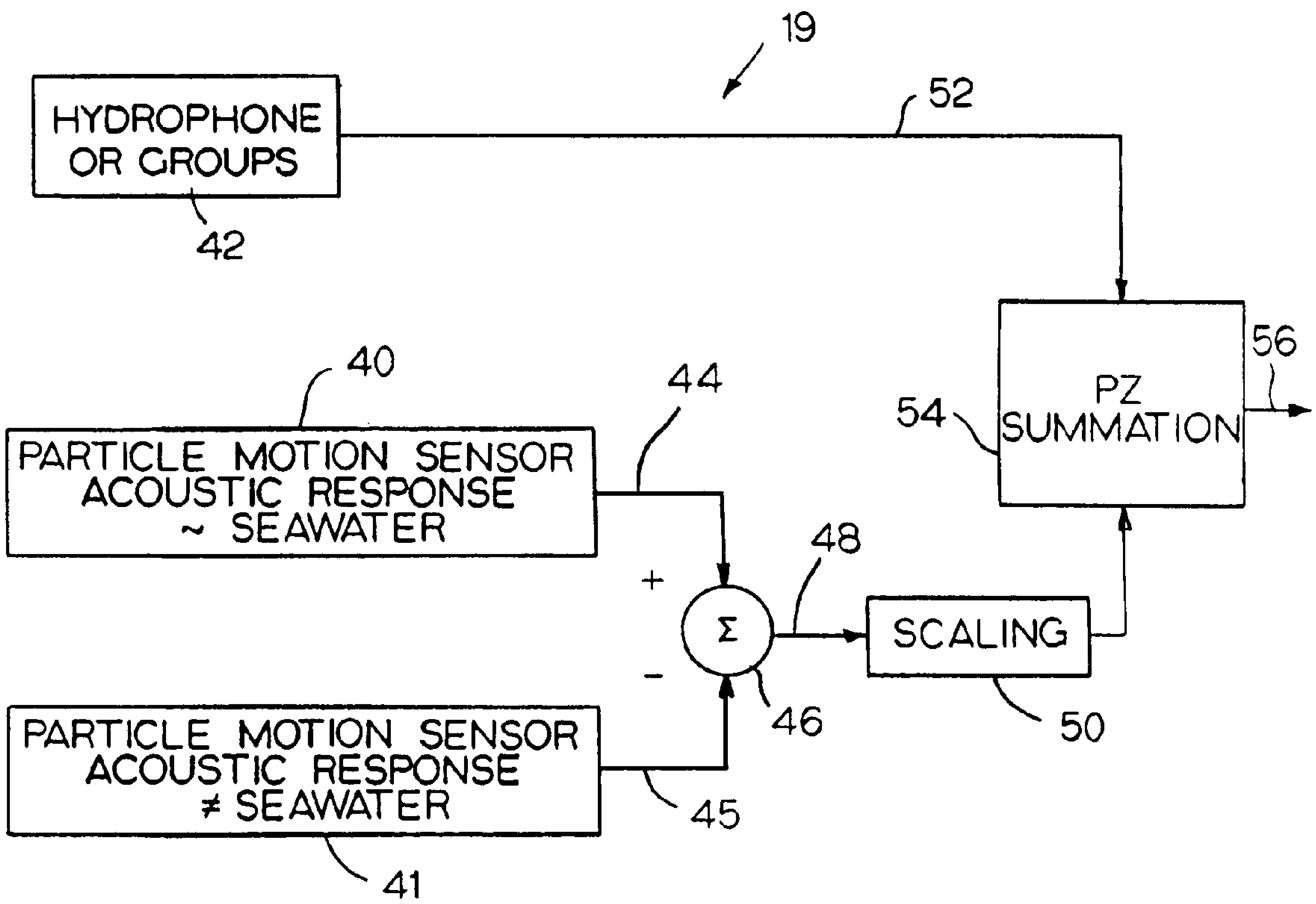
19
HYDROPHONE OR GROUPS
42
52
PZ SUMMATION
54
56
40
PARTICLE MOTION SENSOR ACOUSTIC RESPONSE ~ SEAWATER
44
+
Σ
-
48
SCALING
50
46
PARTICLE MOTION SENSOR ACOUSTIC RESPONSE ≠ SEAWATER
45
41

FIG. 7

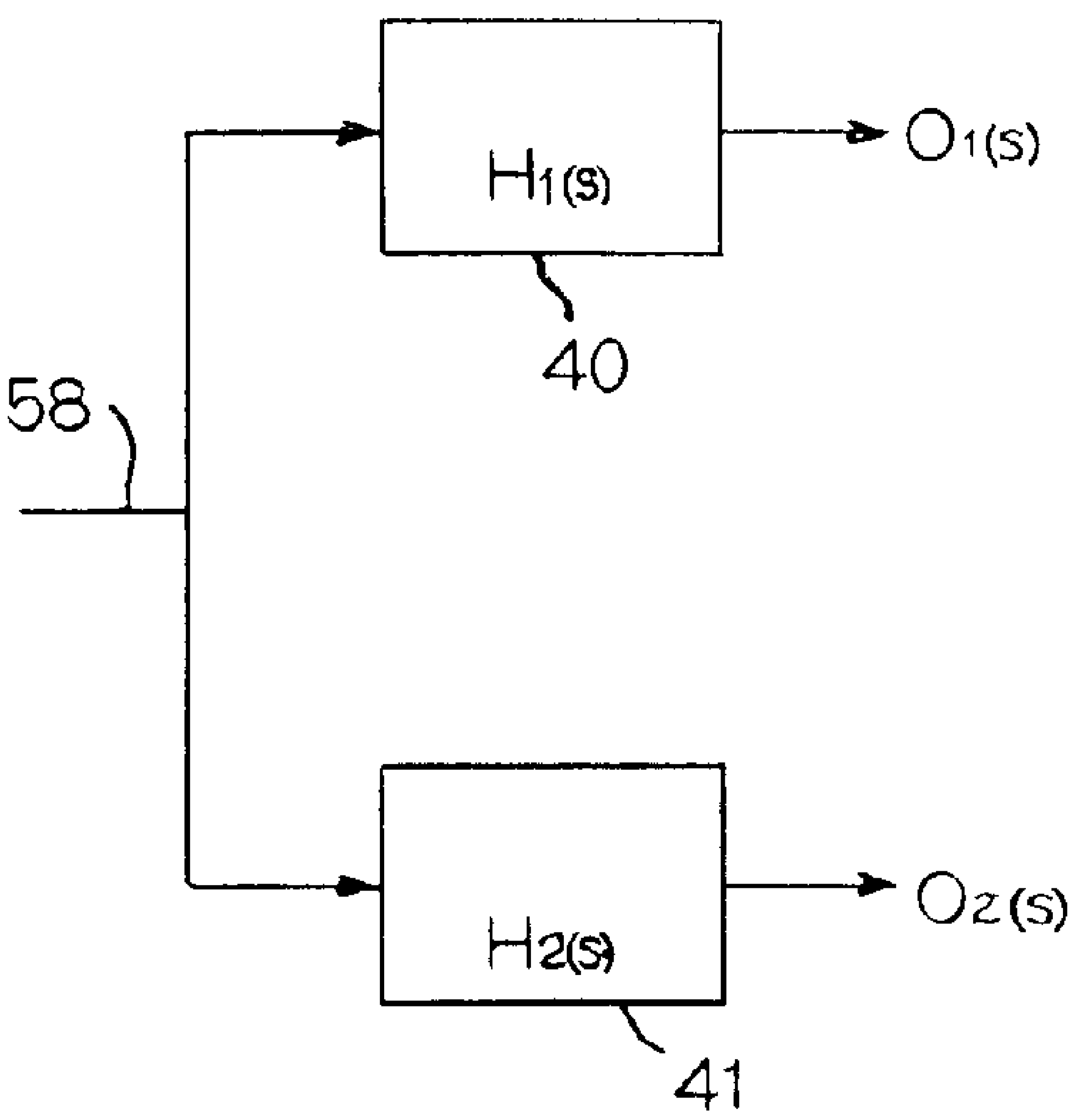

FIG. 8

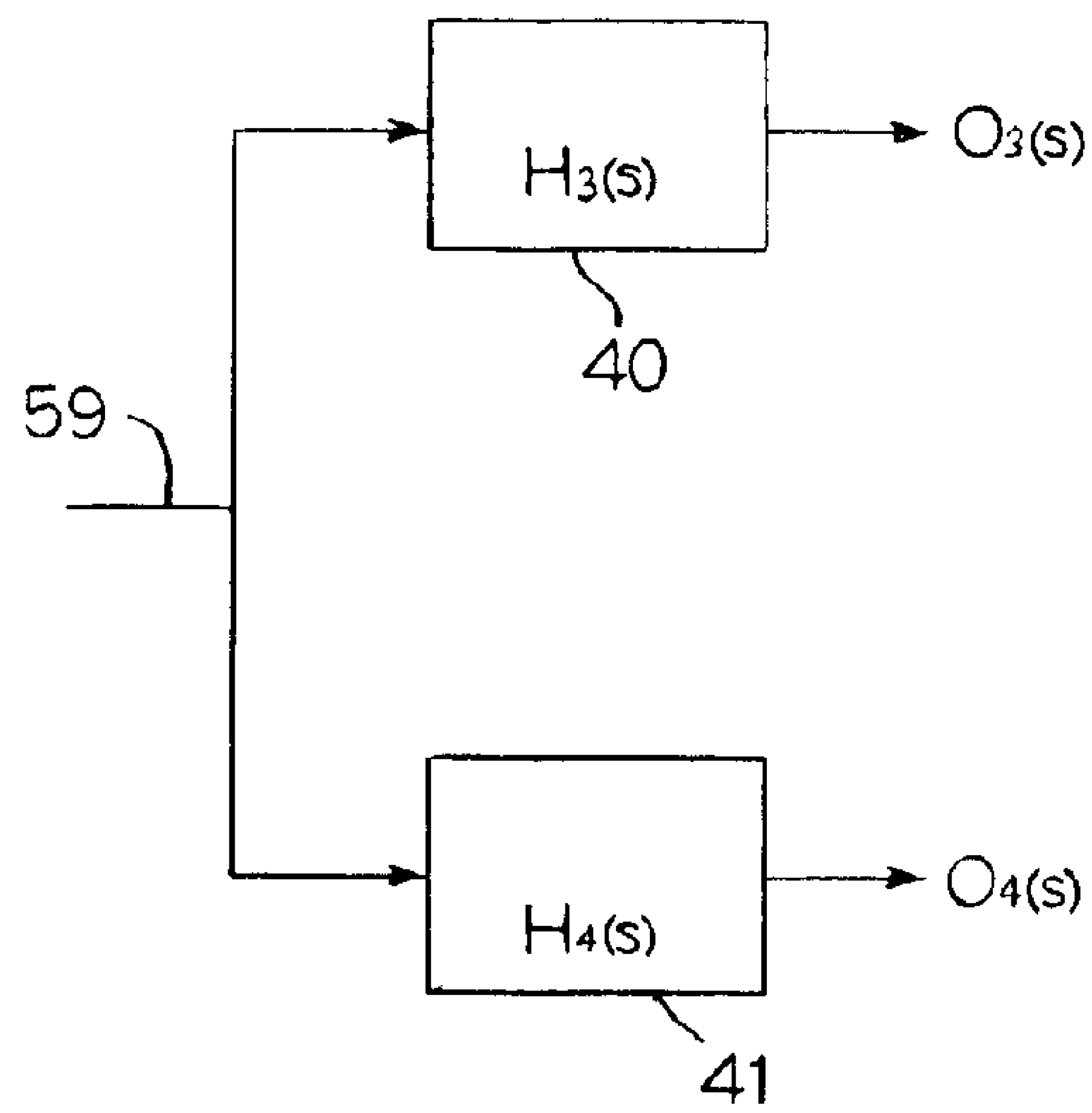

FIG. 9

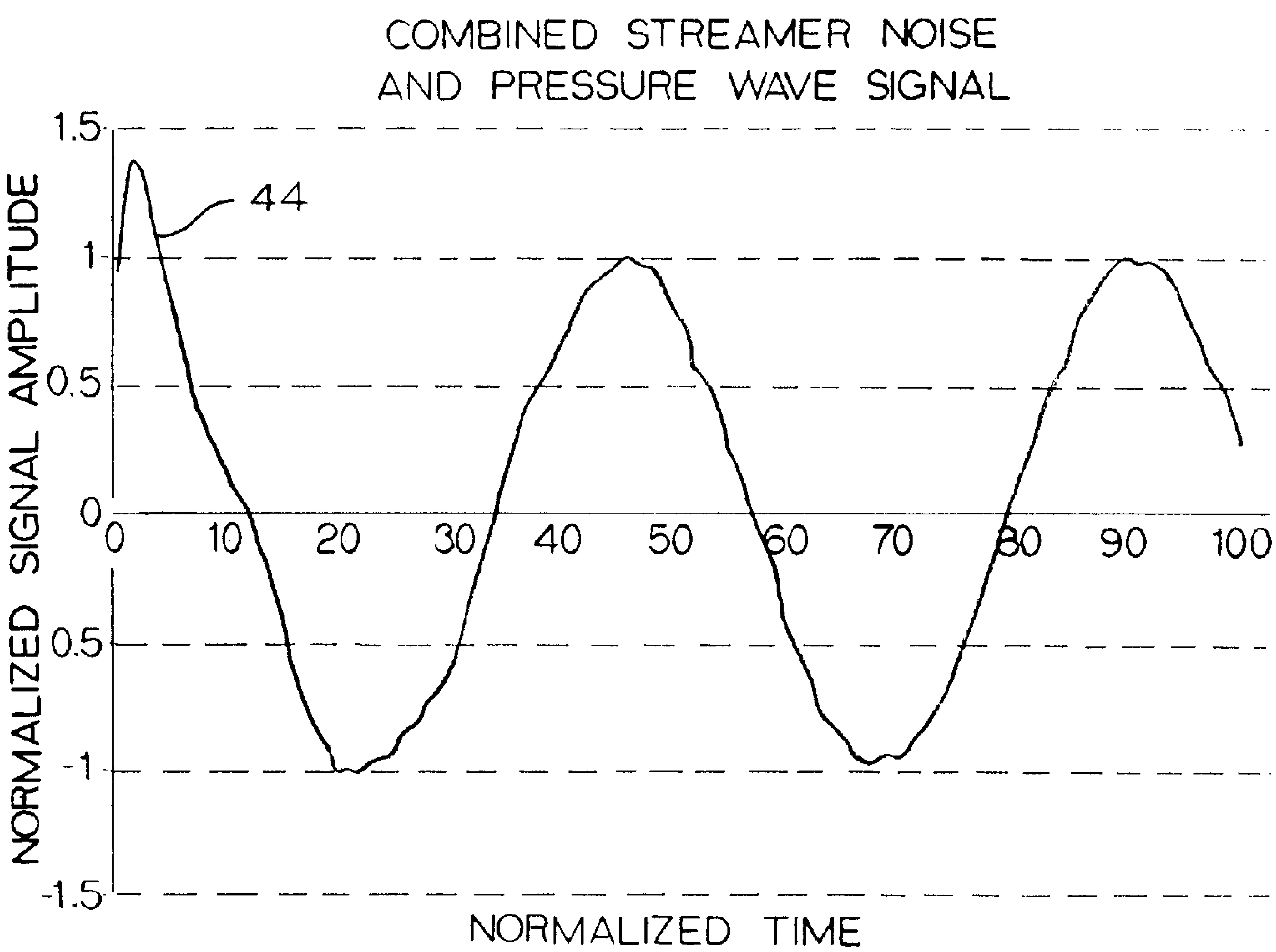

FIG. 10

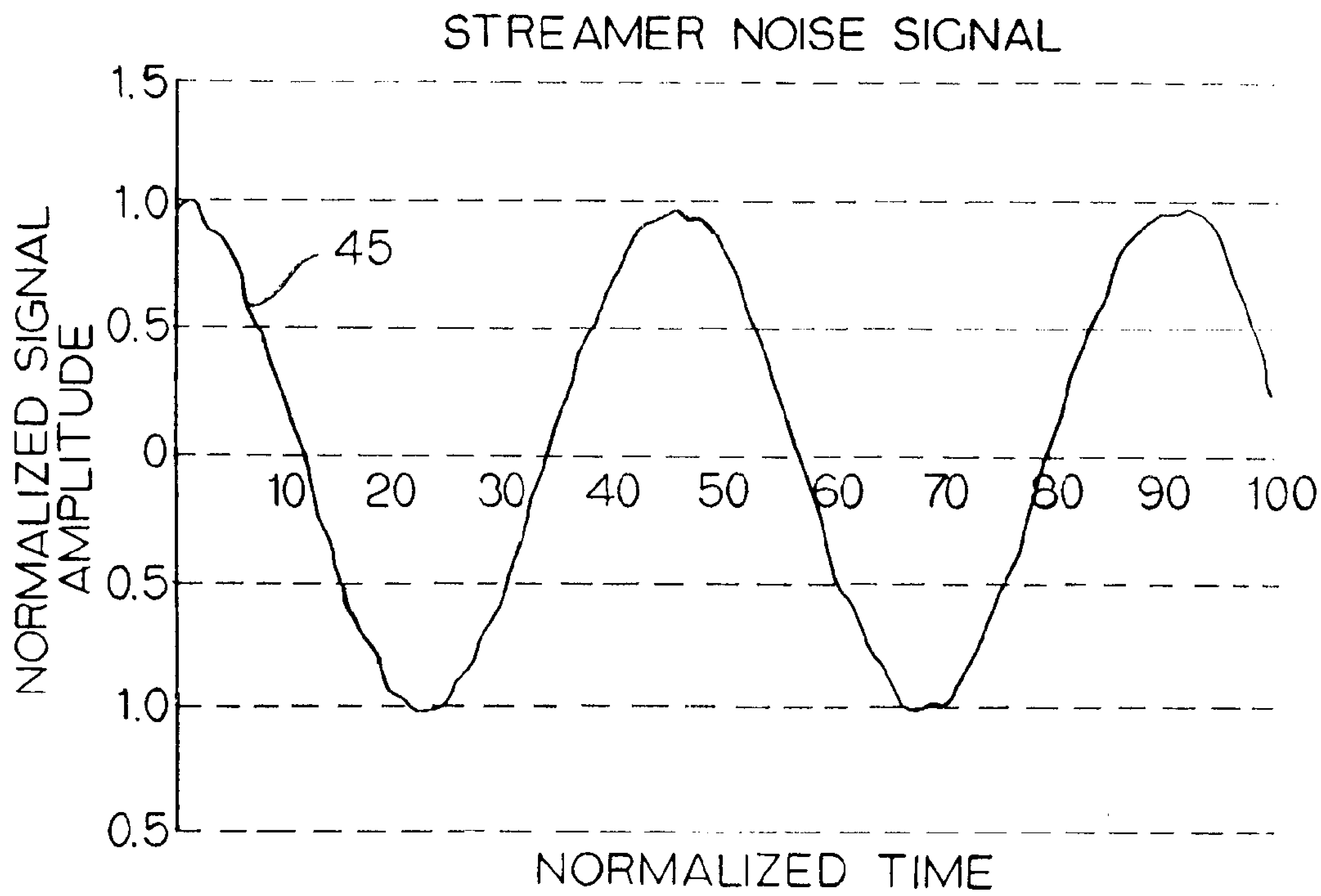
STREAMER NOISE SIGNAL
NORMALIZED SIGNAL AMPLITUDE
1.5
1.0
0.5
0
0.5
1.0
0.5
45
10
20
30
40
50
60
70
80
90
100
NORMALIZED TIME

FIG. 11

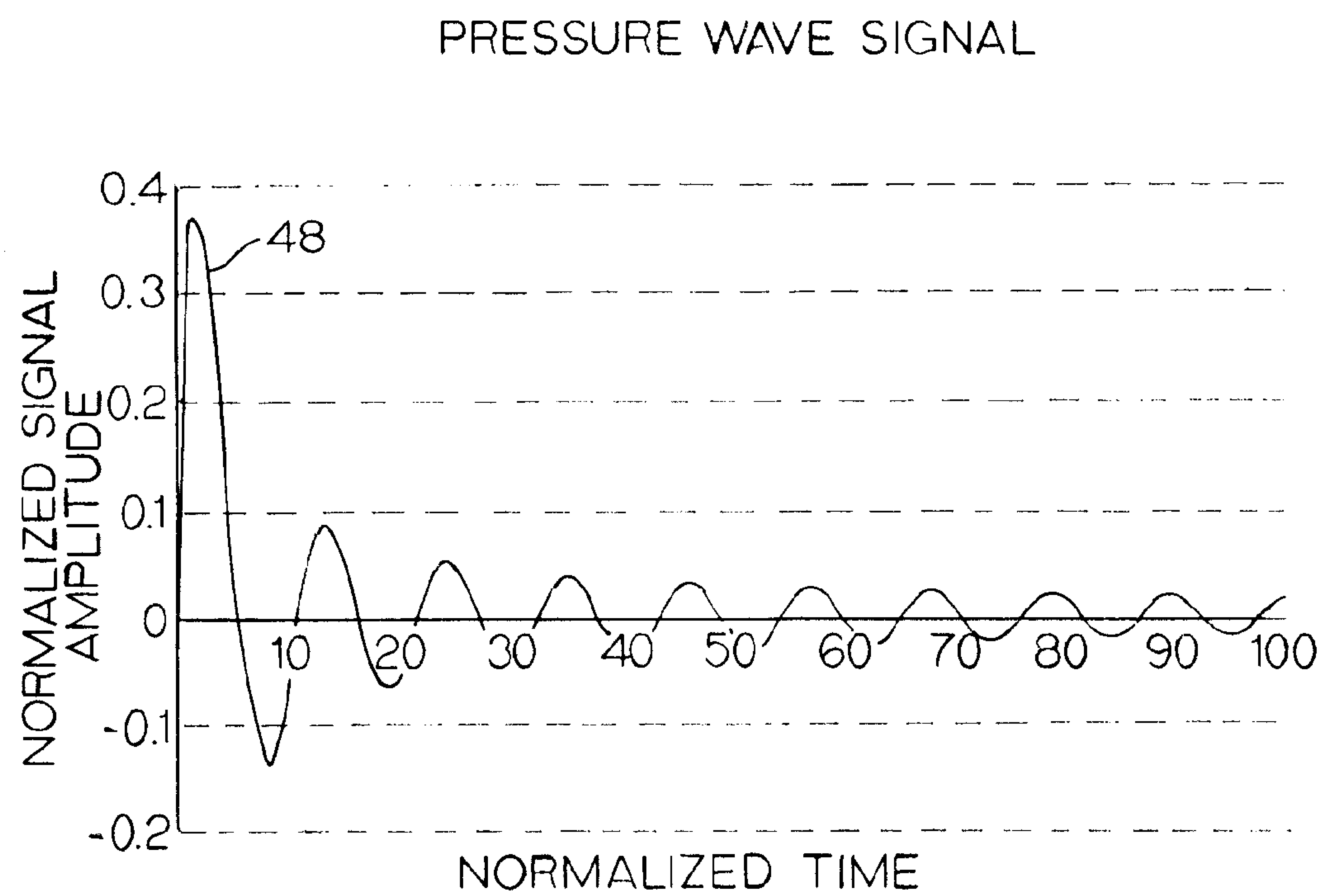
PRESSURE WAVE SIGNAL
NORMALIZED SIGNAL AMPLITUDE
0.4
0.3
0.2
0.1
0
-0.1
-0.2
48
10
20
30
40
50
60
70
80
90
100
NORMALIZED TIME

FIG. 12

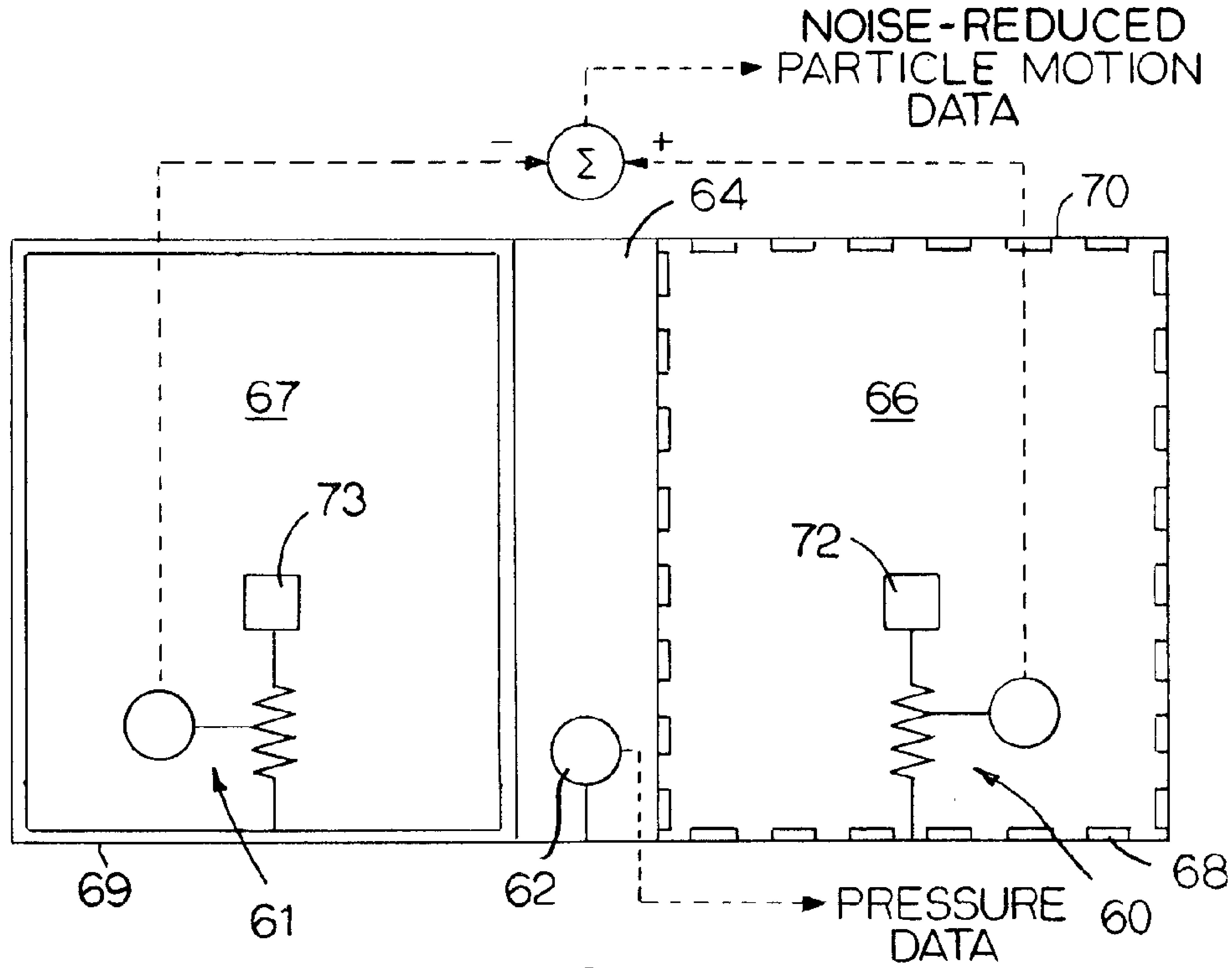

FIG. 13

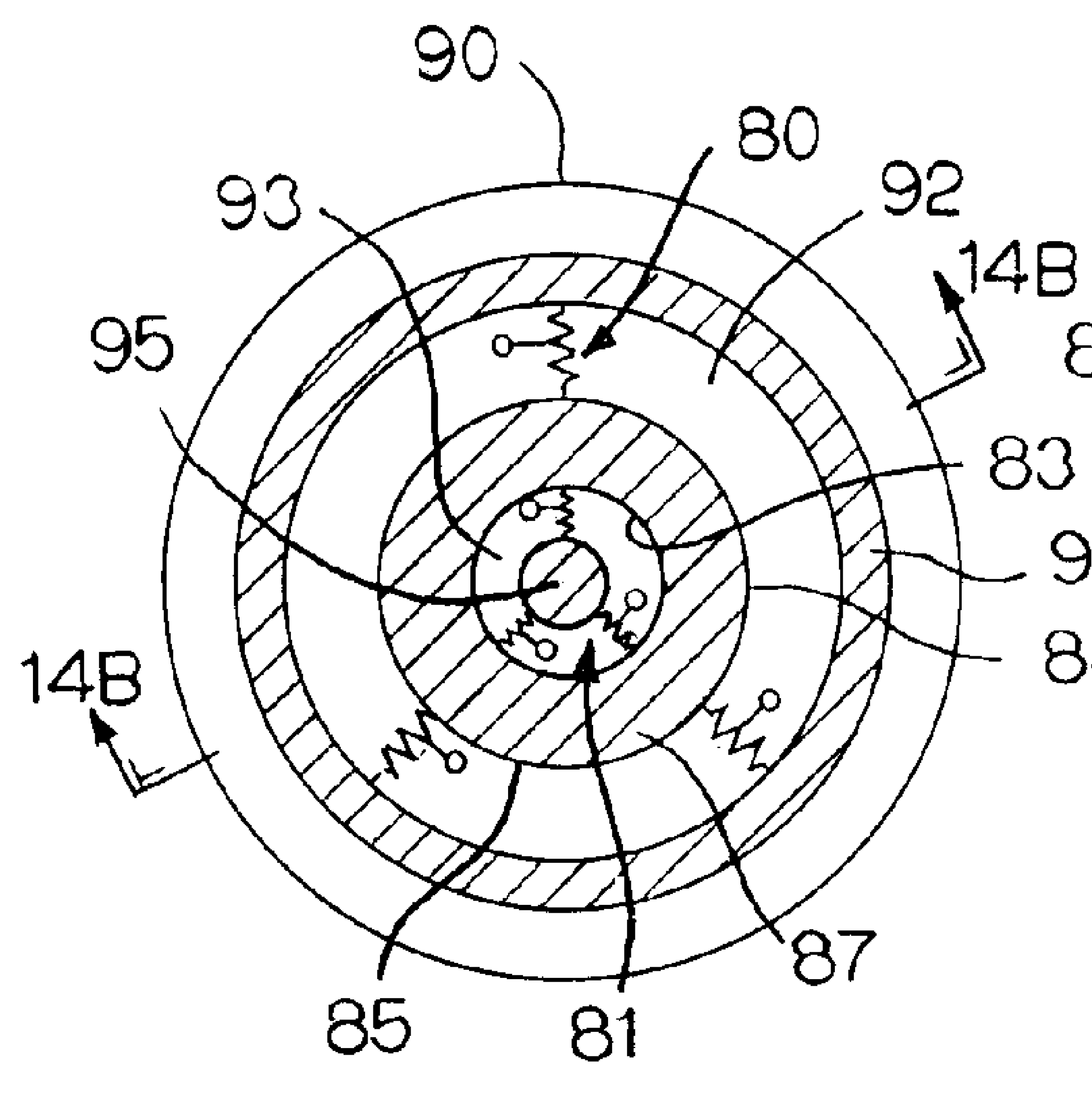

FIG. 14A

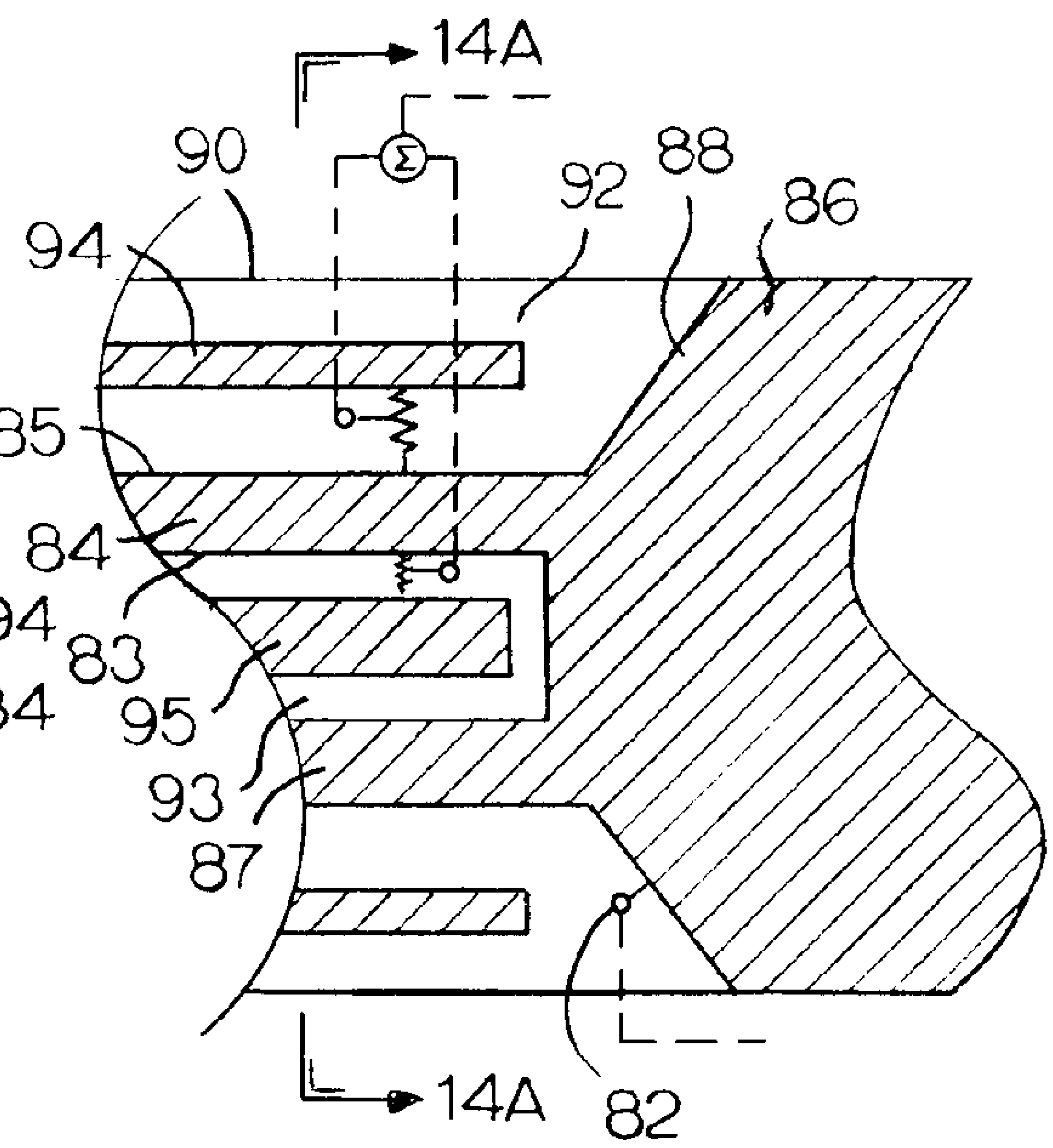

FIG. 14B

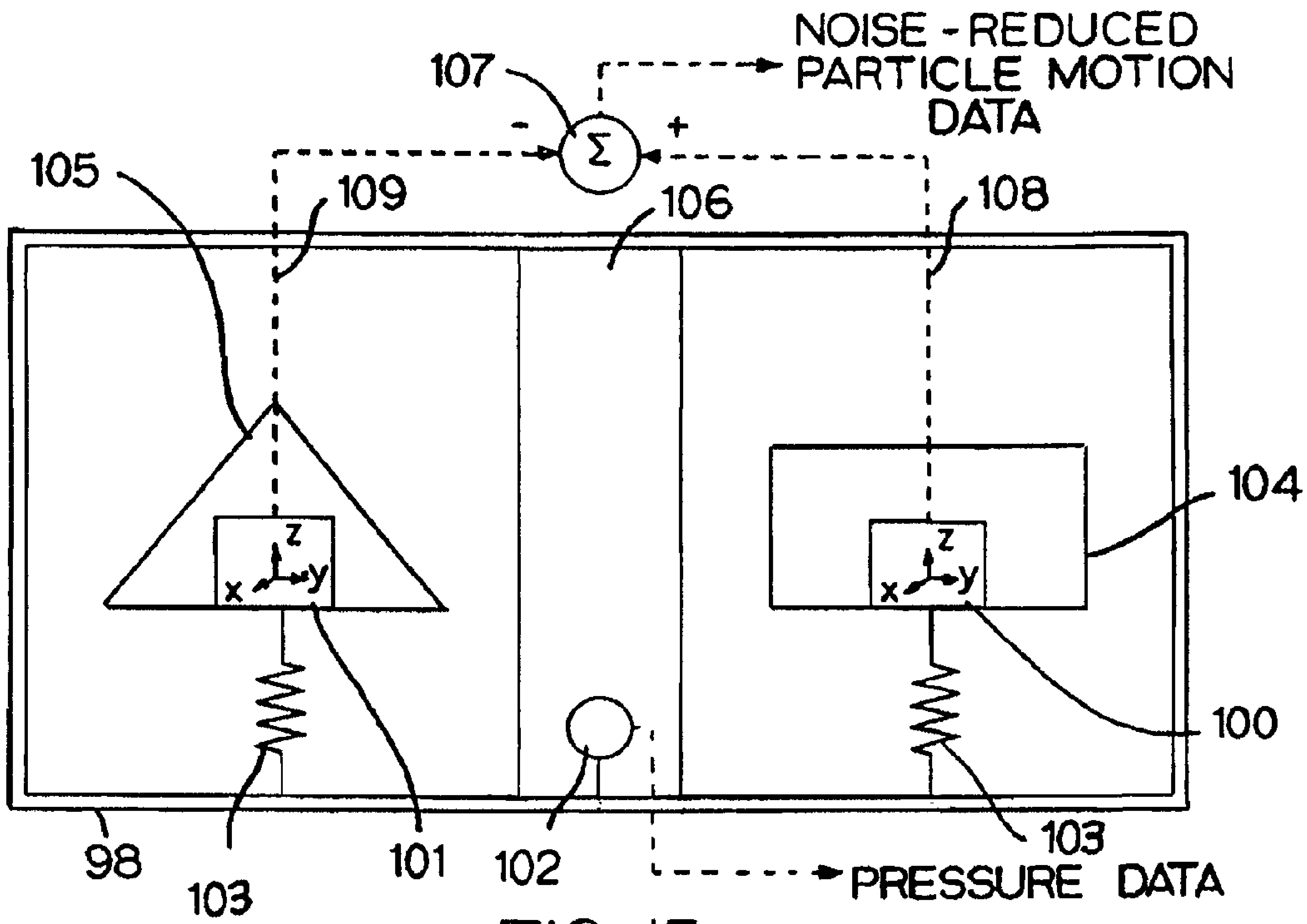
NOISE - REDUCED
PARTICLE MOTION
DATA
107
105
109
106
108
104
100
98
103
101
102
103
PRESSURE DATA

FIG. 15

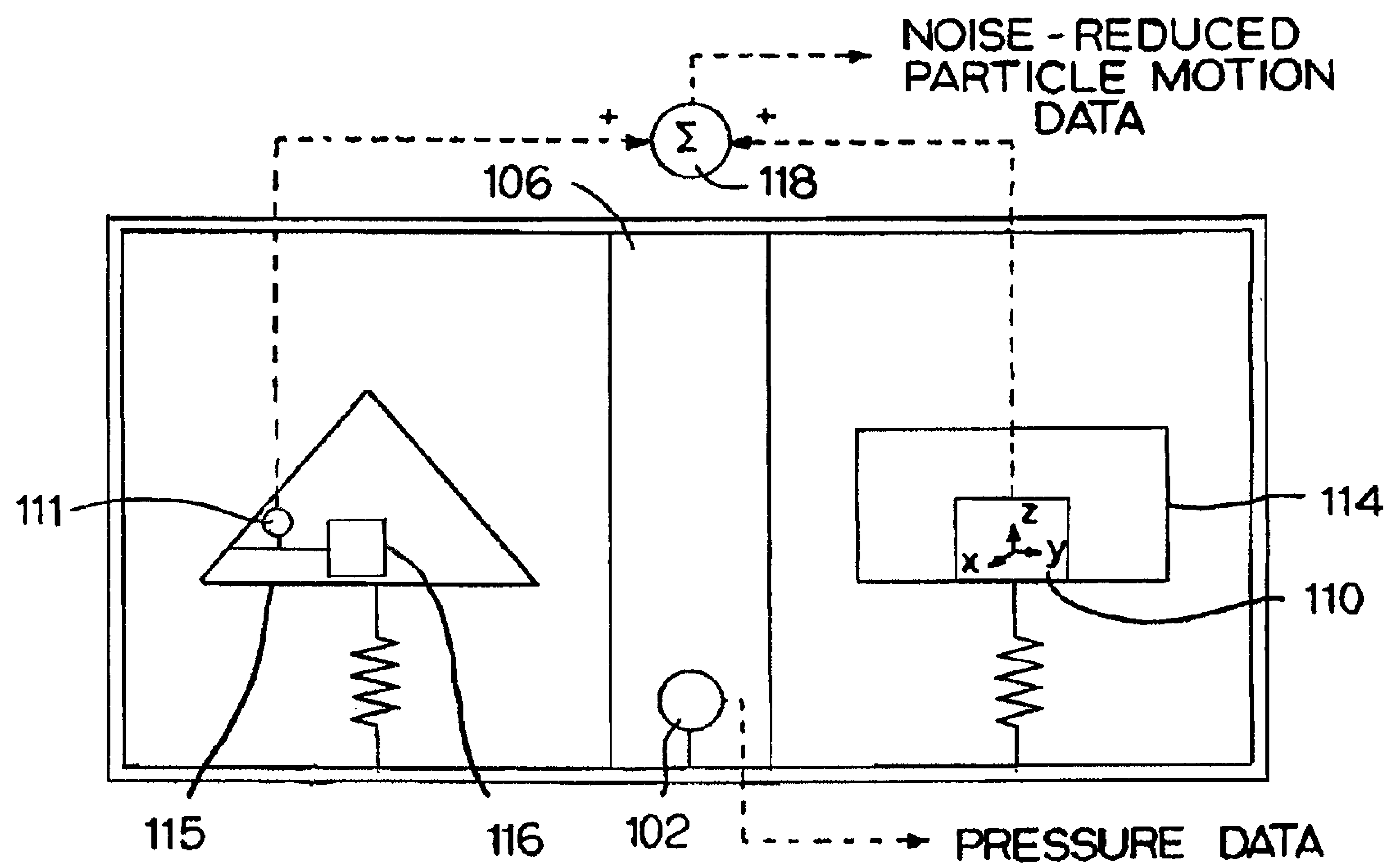
NOISE - REDUCED
PARTICLE MOTION
DATA
106
118
111
114
110
115
116
102
PRESSURE DATA

FIG. 16

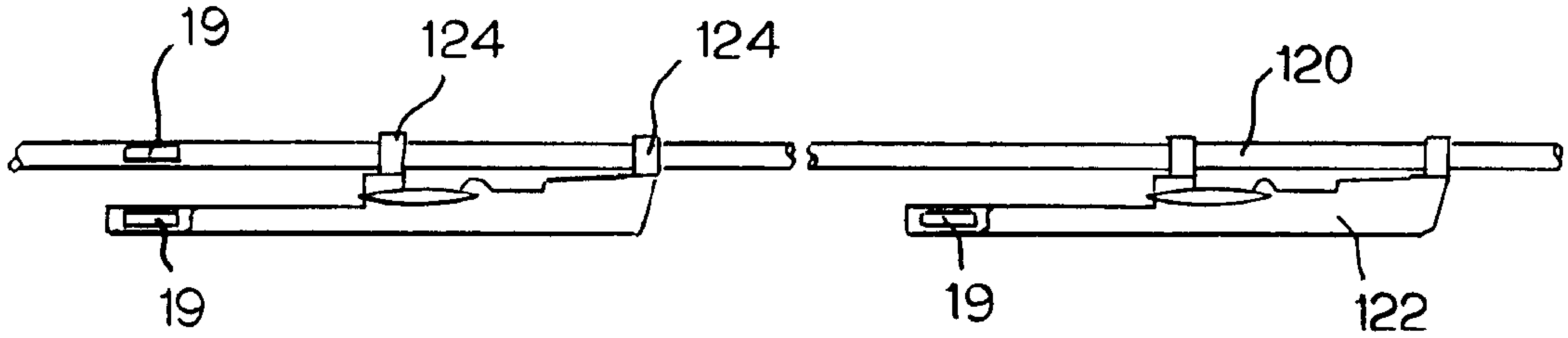

FIG. 17

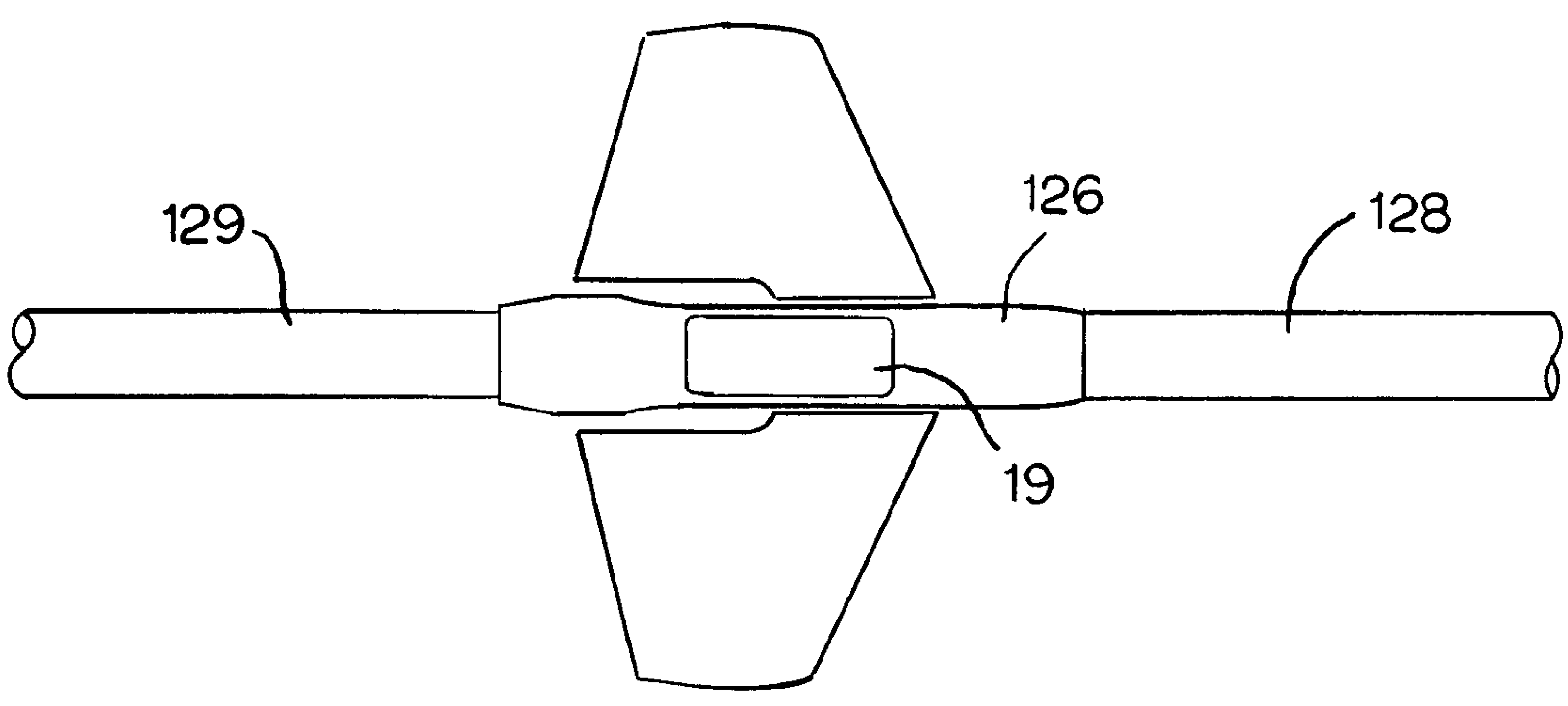

FIG. 18

SEISMIC SYSTEM WITH GHOST AND MOTION REJECTION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application Ser. No. 61/297,656, "Seismic System with Ghost and Motion Rejection," filed Jan. 22, 2010, and incorporated entirely by reference into this specification.

BACKGROUND

The invention relates generally to marine seismic prospecting and in particular to apparatus and methods for reducing the effects of undesired seismic reflections and noise in sensors towed behind a survey vessel, in sensors laid on the sea bottom, or in sensors in autonomous nodes.

In towed marine seismic exploration, a hydrophone array is towed behind a marine vessel **20** near the sea surface **22**, as in FIG. **1**. The hydrophones are mounted in multiple sensor cables commonly referred to as streamers **24**. The streamers serve as platforms for the hydrophones. A seismic sound source **26**, also towed near the sea surface, periodically emits acoustic energy. This acoustic energy travels downward through the sea, reflects off underlying structures or subsea strata **28**, and returns upward through the sea to the hydrophone array. Reflected seismic energy arrives at towed-array receive points. The hydrophone array contains many such receive points and records the upward traveling seismic acoustic wavelet from the seabed **30** at each of the receive points. The hydrophone recordings are later processed into seismic images of the underlying structures.

Noise is a major consideration in towed streamer operations. Noise sources include swell noise and wave noise from the sea surface. And towing the streamer through the water causes noise. Some of this noise propagates through the streamer and some through the water column itself. The typical way of dealing with noise sources is to use a combination of temporal and spatial filtering. Temporal filtering is accomplished by discrete digital sampling of the hydrophone signals in time with weighting applied to the samples. The hydrophone channels also include analog filters to prevent aliasing of signals at frequencies greater than half the sample rate. The spatial samples are typically formed by group-summing individual hydrophone outputs so that pressure noise propagating along the length of the streamer is attenuated. This spatial sampling has no impact on noise that propagates in a direction orthogonal to the streamer axis. Typical hydrophone groups consist of eight or so hydrophones in a 12 m section of the streamer.

Acoustic impedance, ρc, is the product of the density and the speed of sound in a medium. Reflection of at least some of the sound-wave energy occurs whenever a change in acoustic impedance is encountered by the sound waves. The energy that is not reflected is transmitted (refracted) beyond the boundary between the two regions of different acoustic impedances. The pressure waves are compression waves, which induce particle motion in the direction of propagation. At a planar interface between two different homogenous media, a sound wave reflects at an angle equal to the angle of incidence θ_1 and refracts at an angle θ_2. The refraction angle is given by:

$$\theta_2=\sin^{-1}(c_2 \sin \theta_1/c_1).$$

The subscript refers to the sound wave moving from medium **1** to medium **2** and c_1 and c_2 are the speeds of sound in each

medium. If the incident angle θ_1 is zero, then the refracted energy propagation path will be at an angle θ_2 of zero.

For an incident angle θ_1 of zero and no energy converted to shear energy, the reflection coefficient at the water-air interface is described by:

$$R_{pp} = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \approx -1.$$

The reflected energy at the water-air interface is R^2_{pp}, or nearly 1, making the sea surface a near perfect reflector of sound energy. After returning from the sea bottom or the target of interest, the energy is again reflected by the sea surface back to the streamer. Because a typical hydrophone has an omni-directional response, the hydrophone array also records a ghost response, which is the seismic acoustic wavelet reflected from the sea surface and arriving delayed in time and reversed in polarity. The ghost is a downward-traveling seismic acoustic wave that, when added to the desired wave, detracts from the recorded seismic image. The ghost-causing reflection can also continue to the sea bottom or other strong reflector and be reflected back up to again interfere with the desired reflections and further degrade the image. These reflections are commonly referred to as multiples.

For a vertically traveling pressure wave, the ghost produces a notch in the frequency spectrum of a hydrophone response at f_{notch}=c/2d, where c is the speed of sound and d is the streamer depth. Seismic streamers have been conventionally towed at a depth of 10 m or less. At a depth of 10 m, the notch frequency (f_{notch}) is 75 Hz. A frequency response extending beyond 100 Hz is required for high seismic image resolution. Because the notch frequency is inversely proportional to the tow depth, streamers are often towed at shallower depths to improve the resolution of a seismic image. Towing at shallow depths is problematic because noise from the sea surface begins to interfere with the desired seismic signals. These effects are worsened as weather deteriorates, sometimes causing the crew to discontinue operations until the weather improves. The elimination of ghost-notch effects would enable towing at greater depths farther away from surface disturbances.

Ocean bottom systems, in which the seismic sensors are placed on the seabed, reject ghosts and multiples by a technique commonly known as p-z summation. In an acoustic wave, the pressure p is a scalar, and the particle velocity u is a vector. A hydrophone, with a positive omni-directional response, records the seismic acoustic wave pressure p. A vertically oriented geophone or accelerometer records the vertical component of the seismic acoustic-wave particle velocity u_z, with a positive response to up-going signals and a negative response to down-going signals. In p-z summation, the velocity signal is scaled by the acoustic impedance ρc of seawater before it is added to the pressure signal. A gimbaled single-axis sensor is also scaled to account for the change in sensitivity of the particle-motion sensor due to the off-axis arrival of any received signals. If an accelerometer is used, its output signal can be integrated to obtain the velocity signal, or the hydrophone signal can be differentiated so that it can better spectrally match the accelerometer. This produces a compound sensor that has a full response to the upward traveling wave and at least a partially muted response to the downward traveling wave to reject the ghost and multiples. One such method of signal conditioning and combination of signals to get a single de-ghosted trace is described in U.S. Pat. No. 6,539,308 to Monk et al. FIG. **2** is a two-dimensional

(2D) representation of the response of a particle-velocity sensor. FIG. **3** is a 2D representation of the response of an omni-directional hydrophone summed with the response of a vertical particle-motion sensor. The full three-dimensional responses can be envisioned by rotating the 2D responses about their vertical axes.

Recently there has been interest in using techniques similar to p-z summation in towed-streamer acquisition to allow deeper tows without interference from ghost-notch reflections. Operating a particle-motion sensor in a seismic streamer presents a problem because the streamer experiences accelerations due to towing or sea surface effects that are large compared to accelerations caused by the desired seismic reflections. Moreover, these unwanted accelerations are in the same spectral band as the desired reflection response. When a towing vessel encounters ocean waves, there are small perturbations in the speed of the vessel. The vessel also typically undergoes a yawing motion. FIG. **4** depicts energy being imparted to the streamers **24** by speed variations **32** and yawing motion **34**. FIG. **5** is a side view depicting energy causing accelerations and transverse waves in the streamer **24**. (The energy's effect on the streamer is exaggerated in FIG. **5** for illustrative purposes.) Most of the energy is attenuated by elastic stretch members **36**, typically in front of the sensing arrays. While the energy is greatly attenuated, some does remain. Accelerations a caused by planar pressure waves due to the desired seismic reflections are given by:

$$a = \frac{p2\pi f}{Z},$$

where p=the acoustic sound pressure level, f is the frequency, and Z is the acoustic impedance. Performance of a particle-velocity measuring system should be near the ambient noise limits. Typically, seismic-data customers require ambient noise from streamer hydrophone systems to be below 3 μbar. Since the acoustic impedance of seawater is 1.5 MPa·s/m, a 3 μbar pressure wave at 4 Hz produces particle accelerations of roughly 0.5 μg. FIG. **6** shows a mechanical model of the frequency response of typical cable axial accelerations in the middle of a streamer. The presence of a secondary peak at 4 Hz, only 1.5 orders of magnitude below the primary peak, indicates that, in some cases, the cable dynamic motion can be greater than the seismic signal to be measured.

U.S. Pat. No. 7,167,413 to Rouquette uses an accelerometer in a seismic streamer to reject the ghost-notch effect. Rouquette uses a mass-spring system to reduce the effect of cable dynamics on the accelerometer and a load-cell system to measure and reject the cable-motion-induced noise on the accelerometer. The Rouquette system relies on well-known complex mechanical relationships that do not remain constant with manufacturing tolerances, aging, and environmental conditions. Rouquette uses a signal-processing adaptive algorithm to derive the relationship of the load-cell-sensor-and-mass-spring system to the acceleration acting on the accelerometer in situ. Rouquette describes a complex mechanical and electronic system.

U.S. Pat. No. 7,239,577 to Tenghamn et al. describes an apparatus and method for rejecting the ghost notch using an acoustic-wave particle-velocity sensor. Tenghamn et al. teaches the use of a fluid-damped, gimbaled geophone. It is known in the art that the fluid encapsulating the geophone is chosen to provide damping of the sensor swinging on its gimbals. While not described in Tenghamn et al., it is known in the art that a mass-spring vibration-isolation system can reduce the effect of cable mechanical motion on the geophone response. Motion of the geophone caused by cable mechanical motion is indistinguishable from acoustic-wave particle motion in the geophone response. The desired seismic-wave particle motion is obscured by cable mechanical motion in Tenghamn et al. This technique also gives the response similar to the cardioid in FIG. **3**, where there are still undesired signals coming from the surface and being induced by streamer excitation along the streamer axis.

U.S. Pat. No. 7,359,283 to Vaage et al. describes a method of combining pressure sensors and particle-motion sensors to address the impact of mechanical motion on the particle-motion sensors. In this method, the response of the particle-motion sensor below a certain frequency f_0 is not used, but only estimated from the pressure-sensor response and the known pressure-sensor depth. The frequencies rejected are those for which mechanical motion of the streamer is expected. The estimated response has poor signal-to-noise ratio at the lower frequencies of interest. This rejection below a certain frequency is not optimal as it also rejects valid signals in an important low-frequency band where deep-target data is likely to exist.

While these patents all describe methods to reject the ghost notch in a seismic streamer, none adequately addresses the effects of streamer tow and other noise that affects the particle-motion sensor or hydrophone measurements. All also fall short of producing high-fidelity, sensed acoustic-wave components with good signal-to-noise ratio down to the lowest frequencies of interest.

SUMMARY

These shortcomings are addressed by an underwater seismic system embodying features of the invention. Such a system comprises a first motion sensor that can be used on an underwater platform and has a first response and a second motion sensor that is disposed proximate to the first motion sensor and has a second response. The first and second responses are similar in magnitude for platform motion and different for acoustic wave particle motion.

One version comprises a first motion sensor having a first acoustic impedance to produce a first sensor signal representing platform motion and acoustic waves and a second motion sensor disposed proximate to the first motion sensor and having a second acoustic impedance to produce a second sensor signal representing platform motion and representing attenuated particle motion due to acoustic waves. Means for combining the first sensor signal and the second sensor signal attenuates noise due to platform motion and produces a response to particle motion due to acoustic waves.

Yet another version comprises a first motion sensor and a second motion sensor disposed proximate to the first motion sensor. An acoustic shield is arranged to shield only the second motion sensor from acoustic wave particle motion.

BRIEF DESCRIPTION OF THE DRAWINGS

These aspects and features of the invention are better understood by referring to the following description, appended claims, and accompanying drawings, in which:

FIG. **1** is a side elevation view of a typical seismic survey operation showing an array of hydrophones under tow behind a survey vessel and depicting reflected seismic energy arriving at towed-array receive points;

FIG. **2** is a two-dimensional graph of the response of a particle-velocity sensor;

FIG. 3 is a two-dimensional graph of the response of an omni-directional hydrophone summed with the response of a vertical particle-velocity sensor;

FIG. 4 is a top plan view of a typical survey as in FIG. 1 depicting tow-speed fluctuations and yaw;

FIG. 5 is a side elevation view of a survey as in FIG. 4 depicting the exaggerated effects of tow-speed fluctuations and yaw on streamer shape;

FIG. 6 is a plot of typical accelerations of a streamer in a survey as in FIG. 1;

FIG. 7 is a block diagram of a general version of an underwater seismic system embodying features of the invention including two motion sensors with different acoustic responses;

FIG. 8 is a frequency-domain block diagram of the responses of motion sensors as in FIG. 7 to the acoustic-wave component of incident acoustic energy;

FIG. 9 is a frequency-domain block diagram of the responses of motion sensors as in FIG. 7 to the platform-motion component of incident acoustic energy;

FIG. 10 is a time-domain plot of the output of a motion sensor as in FIG. 7 that is responsive to platform motion and acoustic (pressure) waves;

FIG. 11 is a time-domain plot of the output of a motion sensor as in FIG. 7 that is responsive only to platform motion;

FIG. 12 is a plot of the difference between the outputs of FIGS. 10 and 11 representing an acoustic (pressure) wave signal with platform motion removed;

FIG. 13 is one version of a seismic system as in FIG. 7 in which the motion sensors are housed in different structures, which provide different acoustic impedances;

FIGS. 14A and 14B are cross-sectional views of another seismic system as in FIG. 7 having multiple motion sensors axisymmetrically arranged in a streamer;

FIG. 15 is yet another version of a seismic system as in FIG. 7 in which each motion sensor has a different acoustic cross-section to provide different acoustic responses;

FIG. 16 is an alternative version of the seismic system of FIG. 15 with higher gain;

FIG. 17 is a side elevation view of a seismic system as in FIG. 7 mounted in cable-positioning birds rotatably suspended from a streamer; and

FIG. 18 is a side view of a seismic system as in FIG. 7 mounted in a cable-positioning bird connected in line between streamer sections.

DETAILED DESCRIPTION

FIG. 7 is a block diagram of a general version of an underwater seismic system **19** embodying features of the invention, which comprises techniques for using motion sensors, or sensor assemblies, with different responses to sound-wave-induced signals and similar responses to platform, e.g., streamer, cable, or autonomous node, motion to improve the signal-to-noise ratio of data acquired for seismic imaging. In FIG. 7, two motion sensors **40**, **41** and one pressure sensor **42**, generally a hydrophone, provide signals that are combined to produce a noise-reduced and de-ghosted signal. A group of pressure sensors can be used in lieu of a single sensor, e.g., to reduce the noise arising from pressure waves propagating along the streamer axis. The motion sensors ideally are dc-sensitive and are capable of resolving the gravity vector; otherwise, an additional orientation sensor is used. The first motion sensor **40** has a response to acoustic waves that is ideally, but not necessarily, equal to that of seawater; its response may be increased beyond that of seawater if more gain is desired. The second motion sensor **41** has a response to acoustic waves that is measurably different from that of the first motion sensor **40**. This difference in acoustic response can be realized by means of a difference in the material composition or the geometric configuration of the sensors. In all versions of the system, the material and geometric properties of both sensors are chosen so that their mechanical responses to platform motion are matched. For example, if each motion sensor is designed to interact with a cable in the same way as a second-order mass-spring system, then the masses (including added mass, if appropriate) of the sensors and their associated spring constants are made equal. The first and second outputs **44**, **45** of the first and second motion sensors **40**, **41** are subtracted **46**, either locally or after remote processing, to produce a reduced-noise response signal **48** indicating particle motion due to acoustic waves with platform motion attenuated. The subtraction block **46** constitutes one means for combining the first sensor signal and the second sensor signal. If the signal of one of the sensors is reversed in phase, the means for combining the first sensor signal and the second sensor signal would be realized as an addition block instead. The reduced-noise response is scaled **50** to match the pressure-sensor response **52**, e.g., the hydrophone signal, and used in p-z summation means **54** to produce a final output signal **56** that also rejects ghost notches and multiples. The means for combining the first sensor signal and the second sensor signal and the p-z summation means may be realized locally by analog circuitry, by digital logic circuitry, or algorithmically in a microprocessor, remotely in a shipboard computer or in off-line data processing.

FIG. 8 is a block diagram of the two motion sensors **40**, **41** of FIG. 7 in the frequency domain indicating their transfer functions to the acoustic wave component **58** of incident energy. The acoustic wave component includes the seismic signals of interest. The first sensor **40** and the second sensor **41** have unequal acoustic wave transfer functions $H_1(s)$ and $H_2(s)$. The transfer function $H_1(s)$ is sensitive to acoustic wave particle motion, so that the first sensor **40** produces an output response $O_1(s)$ that represents particle motion. The transfer function $H_2(s)$ is insensitive to acoustic wave particle motion, and the second sensor **41** produces an output response $O_2(s)$ that does not include the motion of surrounding acoustic-medium particles. FIG. 9 is a block diagram of the two motion sensors **40**, **41** of FIG. 7 in the frequency domain indicating their transfer functions to the platform-motion component **59** of incident energy. The transfer functions $H_3(s)$ and $H_4(s)$ of the two motion sensors **40**, **41** to platform motion are proportional (or equal) in magnitude, but could be opposite in phase. Thus, both sensors **40**, **41** have similar output responses $O_3(s)$ and $O_4(s)$ to platform motion. The composite transfer functions of the first and second motion sensors **40**, **41** to incident energy are the combinations of $H_1(s)$ and $H_3(s)$ for the first sensor and of $H_2(s)$ and $H_4(s)$ for the second sensor. The composite responses of the two sensors are the combinations of $O_1(s)$ and $O_3(s)$ for the first motion sensor and of $O_2(s)$ and $O_4(s)$ for the second motion sensor. FIG. 10 is an example representation of the time-domain response of the first sensor **40** to incident energy that includes both platform motion and acoustic waves. The first sensor's response **44** is sensitive to both platform noise and the acoustic wave. FIG. 11 is the corresponding response of the second sensor **41** to the same incident energy. The second sensor's response **45** is sensitive only to the platform-noise component of the incident energy. FIG. 12 plots the result of combining the responses of the two sensors by subtracting the output **45** of the second sensor from the output **44** of the first sensor to produce the noise-subtracted acoustic wave signal **48** of FIG. 7. Although, for purposes of simplifying the description, the response of the second sensor to pressure waves was treated as zero, it may have some slight response, or even a negative response, to pressure waves. Furthermore, the first and second sensor outputs may not be exactly matched to streamer vibrations. But, even in these instances, the signal subtraction still results in an acoustic wave response with a greatly attenuated platform-motion response that can be scaled and combined with the hydrophone data by p-z summation.

Various specific versions of the general system indicated in the block diagrams of FIGS. **7-9** use different levels of acoustic impedance to achieve the desired difference in response to acoustic wavelets. As described above, the two motion sensors **40**, **41** and the pressure sensor **42** are mounted in, on, or to a platform. For example, they may be enclosed in an underwater streamer or mounted inside a cable-positioning bird attached to a streamer. The motion sensors are isolated acoustically from each other, but are located close together and separated into individual regions by a divider, for instance. The first motion sensor is enclosed in a first region with an exterior whose acoustic impedance is similar to that of the surrounding seawater so that acoustic waves penetrate the exterior with minimal reflections and act on the sensor. The second motion sensor is located in an acoustically opaque enclosure in a second region and is not affected by incident acoustic waves. The streamer itself, being under tension, has a small and erratic response to the acoustic waves. Any response of the streamer itself to the acoustic waves is recorded as platform motion. Therefore, the first sensor has a proportional response to acoustic waves; and the second sensor has a negligible response. Additionally, the sensor assemblies are calibrated to have matched responses to platform motions, (e.g., streamer vibrations), for instance by equating their masses (including added mass, if appropriate) and associated spring constants if they behave as second-order mass-spring systems. Subtraction, either locally or after remote processing, of the second sensor signal from the first sensor signal accordingly yields the desired acoustic wave signal with greatly attenuated streamer-motion response.

One specific version of the seismic system of FIGS. **7-9** is shown in FIG. **13** with two motion sensors **60**, **61**—separated acoustically by a central divider **64**—and a pressure sensor **62**. The first motion sensor **60** is contained in a first region **66** of the streamer with a rigid, acoustically transparent exterior **68**. For example, the exterior **68** is a perforated, rigid housing covered with a flexible, acoustically transparent skin **70**. The interior of the first region **66** is filled with fluid. Ideally, the skin and fluid both have acoustic impedances equal to that of the surrounding seawater. A first test mass **72** with an acoustic response ideally, but not necessarily, equal to that of the fluid is suspended in the fluid; its response may be increased beyond that of seawater if more gain is desired. The first test mass **72** is connected to the exterior of the streamer by means of a displacement, velocity, or acceleration sensor, which serves as the motion sensor. The first sensor **60** uses the exterior of the streamer as a frame of reference and acts as a spring in coupling the test mass and streamer dynamically. The first sensor can be single crystal or a PZT bender, for instance. If the sensor is a single-axis sensor, multiple test-mass systems can be used to form a tri-axis sensor, with all test masses calibrated to match in both acoustic and dynamic response. An alternative for multi-axis measurement is to connect several sensors to a common test mass for multi-axis measurement as long as the mass sensor responses can be kept independent. The second sensor **61** and a second test mass **73** are connected in an assembly in a second region **67** on the opposite side of the divider from the first region **66**. The second sensor's assembly differs from the first sensor's in that its housing exterior **69** has an acoustic impedance much greater than that of the surrounding seawater and its interior **67** is filled with air to account for any non-negligible elasticity in the housing exterior **69**. Augmenting the effects of the increased acoustic impedance of the second sensor's housing is its rigidity, which allows the housing to act as an acoustic shield, analogous to a Faraday cage in electromagnetism. The acoustic impedance of the second housing exterior **69** is set with a material having a suitably high density or sound speed.

Another version of a seismic system embodying the invention is shown in FIGS. **14**A and **14**B with two sets **80**, **81** of motion sensors and a pressure sensor **82**. In this version, the first sensor set **80** and the second sensor set **81** are connected to a single rigid body **84** that carries streamer vibrations. The rigid body has a large-diameter first portion **86**, a smaller-diameter second portion **87**, and a transition section **88** joining the first and second portions. The smaller-diameter portion **87** is tubular in shape with an inner side **83** and an outer side **85**. The first sensor set **80** encircles a section of the second portion **87** of the rigid body **84** and is connected to its outer side **85**. Three or more individual sensors may be used to constitute the first set **80**. If axisymmetry is not employed, then the first sensor set **80** is instead located alongside the rigid body. An acoustically transparent exterior **90**, which may consist of a flexible membrane over a perforated, rigid housing, separates the sensor system from the surrounding seawater. A first cavity **92**, between the second portion **87** of the rigid body **84** and the exterior **90**, is filled with fluid. Ideally, the exterior **90** and the fluid have acoustic impedances equal to the acoustic impedance of the surrounding seawater. A first test mass **94**, with acoustic properties like those of the first test mass in FIG. **13**, is suspended in the first cavity **92** and encircles the second portion **87** of the rigid body **84**. The first test mass **94** is coupled mechanically to the outer side **85** of the rigid body **84** by the first set **80** of motion sensors with properties like those of the first sensor **60** in the version of FIG. **13**, but with the rigid body **84** as their frame of reference. A second cavity **93** is contained entirely within the tubular second portion **87** of the rigid body **84**. The second cavity **93** contains a second test mass **95** suspended in fluid and coupled to the rigid body **84** by the second set **81** of motion sensors connected to the inner side **83** of the rigid body. The dynamic response of the second set **81** of sensors is calibrated to have a response to streamer vibrations that matches the response of the first set **80**. Unlike the first test mass **94**, however, no requirements are placed on the acoustic response of the second test mass **95**. The rigid body **84** itself acts as an acoustic shield to the second sensor set **81** and is composed of a material with relatively high acoustic impedance. A benefit of this coaxial arrangement is that multiple individual sensors respond to the accelerations of each test mass. Combining the output signals of the motion sensors leads to a more robust estimate of the actual acceleration values. As depicted, the first and second sensor sets **80**, **81** are sensitive to radial motion; an additional test-mass-sensor system may be included in each cavity in alignment with the streamer axis if tri-axis sensitivity is needed.

Yet another version of a seismic system is shown in FIG. **15**. A streamer with a rigid, acoustically transparent exterior **98** has two motion sensors **100**, **101**, such as dc-sensitive, tri-axis accelerometers, and one pressure sensor **102**, such as a hydrophone. The exterior **98** may comprise, for instance, a perforated, rigid housing covered with a flexible, acoustically transparent skin. The accelerometers can be realized by microelectromechanical system (MEMS), PZT, single crystal, or any other technology with similar utility. The motion sensors **100**, **101** are rigidly mounted to first and second rigid housings **104**, **105** to enable direct measurement of any dynamic streamer motion. Both sensors are coupled acoustically to the cable exterior **98**, but are isolated acoustically from each other, for instance, by a central divider **106**. Each of the first and second housings **104**, **105** is constructed such that the mass of the first housing plus the mass it encloses equals the mass of the second housing plus the mass it encloses. The dynamic couplings **103** between the housings and the streamer exterior **98** are designed to act as second-order mass-spring systems with equal spring constants so that the equality of the mass-spring relationships is preserved. On the other hand, the housings have different acoustic cross-sections so that they generate different responses to acoustic pressure waves. Specifically, the first sensor **100** generates a first sensor signal **108** that is a good representation of the acoustic particle motion; the second sensor **101** produces a second sensor signal **109** that is largely insensitive to acoustic waves. The sensor housings are constructed with different geometries, and possibly also with different materials, to effect different cross-sections and, thus, different transfer functions for each sensor. The second sensor signal **109** is subtracted **107** from the first sensor signal **108** either locally or after remote processing, to provide the desired pressure wave signal with greatly attenuated response to streamer motion. Open-cell foam can be used, for example, to serve as the dynamic coupling **103** between each housing **104**, **105** and the exterior **98**. Filled with a fluid calibrated to match the acoustic impedance of the surrounding seawater, the foam can serve also as a transparent acoustic coupling. In this example, the first housing **104** is sealed with respect to the fluid and filled with air to account for any non-negligible elasticity in the housing; and the second housing **105** is perforated or slotted and allowed to fill with the surrounding fluid. The resultant disparity in overall density between the housings accounts for their different responses to incident pressure waves.

A modified version of the seismic system of FIG. **15** intended to enhance the overall gain of the system is shown in FIG. **16**. The first sensor **110** behaves acoustically and dynamically like the first sensor **100** in FIG. **15**. The second sensor **111** produces a response to pressure waves that matches that of the first sensor **110** and a streamer-motion response equal in magnitude but opposite in polarity to that of the first sensor. The first housing **114** and the second housing **115** are constructed as in FIG. **15**, particularly in terms of acoustic cross-section and density, so that they have a similar mass-spring response to cable motion, but a measurably different response to incident acoustic pressure waves. The second housing **115** additionally includes a test mass **116** that is designed to oscillate in a fluid and have an acoustic wave response matching that of the first housing **114**. On the other hand, the response of the test mass to streamer motion is much less than that of the housings because the test mass is suspended in a fluid and the housings are coupled mechanically to the cable exterior. The test mass **116** is connected non-rigidly to the second housing **115** by means of a displacement, motion, or acceleration sensor **111** that uses the second housing as a frame of reference. In this example, a cantilevered accelerometer, composed of piezoelectric materials, is used as the motion sensor. Multiple accelerometers can be employed to form a tri-axis sensor, with each test mass calibrated to match the acoustic response of the first housing **114** in its respective axis. Pressure waves, which impart motion on the test mass **116**, but not on the second housing **115**, are therefore detected positively, i.e., in phase. So pressure signals from the first sensor **110** and the second sensor **111** match in both magnitude and sign. Conversely, streamer vibrations, which influence the second housing **115**, but not the test mass **116**, are detected negatively, i.e., opposite in phase. So vibration signals from the sensors match in magnitude, but have opposite signs. In this case the signals from the two sensors **110**, **111** are combined by addition **118**, rather than subtraction, to produce a greatly diminished streamer-motion response and a simultaneous increase in gain of the acoustic wave response. Alternatively, another cantilevered test mass in the first housing **114** could be used. But, because the first sensor signal would also be reversed in polarity, it would have to be combined with the second sensor signal by subtraction rather than addition.

As shown in FIG. **17**, the sensor portion of the seismic system **19** can be mounted within a streamer cable **120** or within a cable-positioning device, such as a cable-leveling or cable-steering bird **122**, rotatably attached to the streamer by collars **124**. As shown in FIG. **18**, a cable-positioning device **126** connected in line between fore and aft streamer sections **128**, **129** can house the sensor portion of the seismic system **19**. Clearly, the sensors can be mounted in other devices attachable in, on, or to a streamer, an ocean-bottom cable, or an autonomous node.

A tri-axis accelerometer with response to dc similar to the VectorSeis sensor manufactured by ION Geophysical Corporation of Houston, Tex., U.S.A., is suitable for many embodiments of the invention. Since there is no dc component to the seismic wavelet, the dc response of the motion sensor is used to detect the orientation of the sensor relative to gravity. One axis of the sensor is designed to be in the known orientation of the streamer axis. Since the streamer axis orientation is known and the gravity vector is measured, the orientation of the sensor, and thus the arriving sensed seismic wavelet, can be electronically rotated relative to gravity so that up-going seismic wavelets can be accepted and down-going seismic wavelets rejected.

Any sensors that detect motion can be used. The sensors can be any motion sensors responsive to position, velocity, or acceleration. For instance, a gimbaled first geophone, as described by Tenghamn et al. in U.S. Pat. No. 7,239,577, can be combined with a second geophone, packaged so that it has little or no response to an acoustic wave and the same response to streamer motion, to achieve the desired result. Piezoelectric accelerometers can be used, as long as they have adequate sensor performance.

If the sensor cannot determine its own orientation, separate orientation sensors can be included in the sensor systems. Alternatively, mechanical means—such as a gimbal system—can be used to fix the sensors in a known orientation. Winged devices attached to the streamer, sometimes referred to as birds, can also be used to force the sensor into a desired orientation.

The invention is not meant to be limited to use in towed marine streamers. The techniques described can also be used in other platforms, such as ocean-bottom cables and autonomous node systems. Additionally, the sensor systems described can be employed for the gathering of seismic data individually; or they can be strung together and used collectively, their data combining to reduce the impact of local flow patterns.

What is claimed is:

1. An underwater seismic system comprising:

a first test mass and a second test mass suspended in an underwater platform;

a first rigid housing rigidly coupled to the underwater platform and enclosing a first interior region in which the first test mass resides;

a second rigid housing disposed proximate to the first rigid housing and rigidly coupled to the underwater platform and enclosing a second interior region in which the second test mass resides;

a first motion sensor housed in the first region and coupling the first test mass to the first rigid housing to provide a first response responsive to the motion of the first test mass;

a second motion sensor housed in the second region and coupling the second test mass to the second rigid housing to produce a second response responsive to the motion of the second test mass;

wherein the second rigid housing and the second region provide an acoustic impedance that is the same as that of seawater to admit acoustic waves into the second region to be sensed by the second test mass;

wherein the first region of the first rigid housing is filled with a material such as air or an open-cell foam that has an acoustic impedance more closely matched to the acoustic impedance of air than to the acoustic impedance of seawater to provide a lower acoustic impedance than that of the second rigid housing and the second region, the lower acoustic impedance shielding the first test mass from acoustic waves;

wherein the first and second responses are similar in magnitude for platform motion and different in magnitude for acoustic waves.

2. An underwater seismic system as in claim **1** further comprising a divider disposed between the first and second motion sensors.

3. An underwater seismic system as in claim **1**,

wherein the first rigid housing is perforated and covered with an acoustically transparent skin.

4. An underwater seismic system as in claim **1** further comprising a fluid filling the first region and having an acoustic impedance equal to that of seawater and air filling the second region.

5. An underwater seismic system as in claim **1** wherein the second rigid housing is made of a high-density material.

6. An underwater seismic system as in claim **1** further comprising:

a plurality of the first motion sensors coupled to the first rigid body and a plurality of the second motion sensors coupled to the second rigid body.

7. An underwater seismic system as in claim **6** wherein the first rigid body has a tubular shape.

8. An underwater seismic system as in claim **7** wherein the first region and the second region are coaxially arranged.

9. An underwater seismic system as in claim **1** further comprising:

a divider disposed between the first and second rigid housings to acoustically isolate the first and second motion sensors;

wherein the first and second rigid housings have different acoustic cross sections to incident acoustic waves.

10. An underwater seismic system as in claim **1** comprising a fluid-filled open-cell foam in the second region and wherein the acoustic impedance of the fluid-filled open-cell foam matches the acoustic impedance of seawater.

11. An underwater seismic system as in claim **1**,

wherein the second test mass disposed inside the second rigid housing is non-rigidly coupled to the second rigid housing by the second motion sensor; and

wherein the first and second motion sensors respond in phase to acoustic waves and opposite in phase to platform motion.

12. An underwater seismic system as in claim **1** wherein the first motion sensor produces a first sensor signal and the second motion sensor produces a second sensor signal, the underwater seismic system further comprising means for combining the first sensor signal and the second sensor signal to attenuate noise due to platform motion and produce a response due to acoustic waves.

13. An underwater seismic system as in claim **12** wherein the means for combining the first sensor signal and the second sensor signal subtracts the second sensor signal from the first sensor signal.

14. An underwater seismic system as in claim **12** further comprising a hydrophone sending a hydrophone signal and means for combining the hydrophone signal with the response due to acoustic waves for removing multiples or attenuating ghost responses.

15. An underwater seismic system as in claim **14** wherein the hydrophone and the first and second motion sensors are in close proximity.

16. An underwater seismic system as in claim **12** further comprising a hydrophone producing a hydrophone signal and p-z summation means for combining the response due to acoustic waves and the hydrophone signal to produce a seismic response signal.

17. An underwater seismic system as in claim **1** comprising a sensor cable serving as the underwater platform, wherein a plurality of the first and second motion sensors are disposed along the sensor cable at spaced apart locations.

18. An underwater seismic system as in claim **1** comprising a cable-positioning device serving as the underwater platform, wherein the first and second motion sensors are mounted in the cable-positioning device.

19. An underwater seismic system as in claim **1** wherein the first motion sensor is disposed in a first medium filling the first region and having a first density and wherein the second motion sensor is disposed in a second medium filling the second region and having a second density greater than the first density.

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